PRACTICAL LIMITATIONS TO THE RANGING ACCURACY ACHIEVABLE WITH A MODULATED CW LASER*

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ABSTRACT

The distance measuring technique which is at present capable of achieving the highest accuracy for intermediate ranges in the earth's atmosphere involves the measurement of modulation phase shift of modulated light. In order to experimentally assess the limitations of this technique, a laser transmitter-receiver system was constructed and operated in conjunction with a fixed-position passive retroreflector target. The optical path was over suburban terrain at tree-top height, and the one-way path length was approximately three kilometers.

Since the true distance to the target was not known, the variation in the measured distance at different times and under diverse atmospheric conditions was used as a measure of ranging accuracy. Errors ascribable to the modulation and detection hardware were assessed in order to determine the error contributions caused by the atmospheric variability over the optical path, and the measured values of phase shift are corrected for atmospheric temperature, pressure, and humidity effects. Measurements of the rapid fluctuations of received signal phase and amplitude caused by atmospheric turbulence were also made for each distance measurement run to permit analysis of turbulence effects.

INTRODUCTION

The measurement of distance by means of modulated light involves a comparison of the relative modulation phase shift between transmitted and received beams. Since such a measurement gives no information as to the number of whole modulation wavelengths traversed by the path, additional measurements at other modulation frequencies are necessary to resolve the ambiguity, however the measurement precision is not affected by these additional measurements. The conversion from phase to distance traversed is effected by the relationship

$$\Phi = 2\pi f_m t = 2\pi f_m L\left(\frac{n_G}{c}\right) \qquad (1)$$

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where Φ is total elapsed modulation phase
f_m is modulating frequency
t is time
L is the range or distance traversed
c is the velocity of light
n_G is the group index of refraction of the medium through which the beam is traveling.

Equation (1) indicates that the precision with which range can be measured will be limited by the accuracy with which the modulating frequency f_m and the group index n_G can be determined, while n_G in turn varies with the atmospheric composition and density along the path. If the measurement path is horizontal and near the surface of the earth, atmospheric turbulence effects will complicate the phase measurement process because the received beam will exhibit scintillation, beam wander, loss of coherence, and other effects ascribable to local inhomogeneities in the atmosphere traversed by the beam. In addition, the inhomogeneity of a turbulent atmosphere tends to reduce the accuracy to which the group index of refraction can be determined. In order to experimentally determine the ranging accuracy achievable under conditions of strong turbulence, a ranging device was constructed and operated over a fixed path to measure the repeatability of a distance measurement with varying atmospheric conditions.

EXPERIMENTAL PROCEDURE

The ranging device constructed consists of a combined receiving-transmitting system mounted along a common axis. A 6328Å He-Ne CW laser, Pockel's cell modulator, and beam expanding telescope make up the transmitting system. The receiving system consists of a 6 inch receiving telescope focused through an adjustable iris and a narrowband optical filter onto a photomultiplier cathode. The modulation phase and amplitude are read via a phase comparator-voltmeter and recorded by a high-speed chart recorder. The modulation frequency used was approximately 25 MHz, and was counted to an accuracy of 0.1 ppm.

The transmitter-receiver unit was aimed through a fourth-floor window at a 2.5 cm aperture corner-cube retroreflector mounted on the roof of a silo approximately 3 kilometers distant. The intervening terrain was flat and developed in typical suburban fashion, and the average path height was at the tree-top level of approximately 15 meters. A reference retroreflector was mounted at the transmitter-receiver site to permit the determination of fixed phase shifts; the actual distance measured was the distance separating the remote retroreflector from the reference one.

In investigating the equipment characteristics it was observed that the electron transit time varied with the position of the light beam upon the photomultiplier cathode [1]. A diagram of measured transit time variations in nanoseconds versus position on the cathode of an RCA 7265 photomultiplier operated at 1000 Volts is shown in Figure 1. These transit time variations can result in phase variations of up to 15 degrees for a modulation frequency of 25 MHz. For distant targets, where the return beam expands to cover the whole photomultiplier surface, these variations are averaged out but still cause rapid fluctuations in the measured phase because of the turbulence-induced beam dancing and scintillation on the photomultiplier cathode. For the close-up reference reflector the beam normally occupies only a small portion of the photomultiplier surface and erroneous readings can result. This difficulty is circumvented by mounting a diffuser in front of the photomultiplier cathode in order to diffuse the beam across the whole cathode surface. The photomultipliers' overall transit time is a strong function of the operating potentials applied to its dynodes, so that the modulation phase changes about 0.2 degree for a 1 Volt change in tube operating potential and a modulation frequency of 25 MHz. This source of error was reduced to negligible proportions by employing a regulated high voltage power supply, a Keithley Model 242, whose specified stability is 0.01%.

It was also observed that for frequencies close to a mechanical resonance of the modulator, a Spectra-Physics Model 320 Pockels effect device, large variations of modulation phase across the beam can result. The 25MHz frequency used as the modulating signal was sufficiently far from the resonant frequency that the variations of modulation phase across the beam cross-section were entirely negligible, however.

The phase comparator used with the system, a Hewlett-Packard 8405A Vector Voltmeter, has a precision of about 0.1 degree but a considerably lesser accuracy. Since only repeatability was needed for this experiment, considerable care was taken to attenuate the signal from the reference retro-reflector to the same level as the average return from the remote target for every measurement. The phase measurements were then always performed on the same scales, so that the limitation was one of circuit stability rather than accuracy.

The distance of a target is computed from the equation given below:

$$2L = (m + \alpha)\lambda_m \tag{2}$$

where L = Target distance

m = Number of whole wavelengths in a round trip to the target

α = Fraction of a wavelength corresponding to phase measurement

λ_m = modulation wavelength.

The modulation wavelength is determined by the modulation frequency and the group refractive index. The modulation frequency was measured to an accuracy of 0.1 ppm. The refractive index depends upon the average temperature, pressure, and humidity of the path and was computed using an empirical formula derived by Owens [2]. Variations in the index on the order of 1 ppm/degree C result from variations in the average path temperature, with lesser errors for pressure and humidity errors. The temperature was measured at the location of the transmitting-receiving system. Since the temperature was measured at only one point of the optical path, part of the ranging error is due to errors in the average path temperature. For instance, it was observed that the measured temperature deviated as much as one degree from that of a fixed meteorological station located only a block from the system. The values of atmospheric pressure and humidity used in correcting the group index were measured at this meteorological station.

Since the phase measurement gives only the value of α, the distance 2L must be known to at least within $\lambda_m/2$. In order to measure the distance to the required accuracy, phase measurements were made at a number of lower frequencies close enough together so that m was the same for each of these frequencies. By plotting $1/\lambda$ versus α, the slope gives L to an accuracy fine enough to determine m for these lower frequencies. Then using one of these lower frequency measurements, L can be computed to the accuracy required by the higer frequency.

RESULTS AND CONCLUSIONS

Table 1 shows distance measurement results taken over a three week period and thus under a variety of weather conditions. The coefficient of variation (standard deviation/average) of the photomultiplier D.C. current output when measuring the return from the remote retroreflector was used as a relative measure of turbulence. This value was computed for a 2 second interval in each case. The D.C. currents listed show the relative signal levels of the measurements. The photomultiplier is operated at an anode potential of 1500 Volts in every instance. All distance measurements were made over the same path. The values of atmospheric pressure for this set of measurements varied over a range of 0.6 inches of Hg, the temperature varied over a range of 6 degrees C., and the coefficient of variation varied from 31% to 125%. The standard deviation of the distance measurements was 2 ppm with a maximum deviation of 4.8 ppm and a minimum of 0.2 ppm.

TABLE 1

Laser Ranging Data

Run	Date	Time	T(°C)	P(in.Hg)	Coeff. of Variation(%)	Distance Deviation(ppm)	D.C.Signal Level(μA)
1	Dec. 18	1:45p.m.	11.4	28.26	62	-1.2	2.1
2	Dec. 18	3:30p.m.	7.4	28.36	92	+4.8	2.5
3	Dec. 18	4:00p.m.	6.7	28.38	41	+0.7	4.3
4	Dec. 18	4:40p.m.	5.8	28.40	33	-0.2	3.8
5	Dec. 19	5:00p.m.	6.8	28.83	57	-2.6	2.3
6	Dec. 20	3:30p.m.	10.5	28.73	36	-1.7	0.9
7	Jan. 2	5:00p.m.	10.6	28.82	38	+1.4	0.7
8	Jan. 6	4:15p.m.	10.6	28.80	125	+2.4	1.4
9	Jan. 6	4:30p.m.	10.6	28.81	72	+0.2	1.3
10	Jan. 6	4:45p.m.	10.1	28.80	33	-3.1	1.7
11	Jan. 7	4:10p.m.	9.7	28.60	31	-1.9	0.6
12	Jan. 8	4:30p.m.	5.9	28.44	42	-0.2	2.0
13	Jan. 8	4:45p.m.	5.9	28.46	47	+1.9	1.5

Most turbulence descriptions are in terms of Tatarski's [3] refractive index structure constant C_N^2, which is related to scintillation at a point detector by the relation

$$\langle (\ln \frac{A}{A_o})^2 \rangle = 0.31 C_N^2 K^{7/6} L^{11/6} \tag{3}$$

where A is the signal amplitude (not intensity)
A_o is the average value of A
K is the wave number $2\pi/\lambda$
L is the path length

under conditions delineated in Tatarski [3]. Davis' [4] aperture averaging curves suggest that our particular two-way path can be approximated as a one-way path with no aperture averaging. The computation of a structure constant in this manner indicates that our worst case of turbulence included in Table 1 (125% coefficient of variation) corresponds to a value of C_N^2 of 3×10^{-15}, which Fried [5] characterizes as a typical intermediate value of turbulence. Actually, we have recorded somewhat stronger values of turbulence on occasion, but the extreme variability of the resulting phase data makes it difficult to meaningfully average this data.

As can be seen from the recorder trace of Figure 2, large variations can occur in instantaneous return signal strength. Since it was known that the phase reading of the phase comparator varied with signal level, the average phase was not directly computed. An average phase for an arbitrarily chosen particular signal level was computed from the trace in order to minimize this effect upon the phase measurement. The same level was used for all phase measurements. The particular case shown in Figure 2 represents a portion of the trace taken for run number 8 of Table 1, a relatively high turbulence case. It can be seen from Figure 2 that the signal level ranges from a relatively low level return to a strong peak many times larger than the low level. This is typical of more turbulent periods in that it shows a weak average return signal with large pulses.

Figure 3 is a portion of the recorder trace of the phase and amplitude measured for the return from the close-up reference retroreflector; it represents the phase and amplitude jitter in the absence of atmospheric turbulence effects.

The results shown in Table 1 do not indicate that the distance deviations are correlated with any of the variables measured, which would imply that the deviations are caused by instrument noise, most likely in the phase comparator. A correlation of deviations with turbulence was expected, since a high degree of turbulence normally corresponds to an extremely sunny but static situation in which the temperature measured at one point is unlikely to be typical of the average path temperature. The data indicates that this correlation might be present, but additional data would be necessary for any verification.

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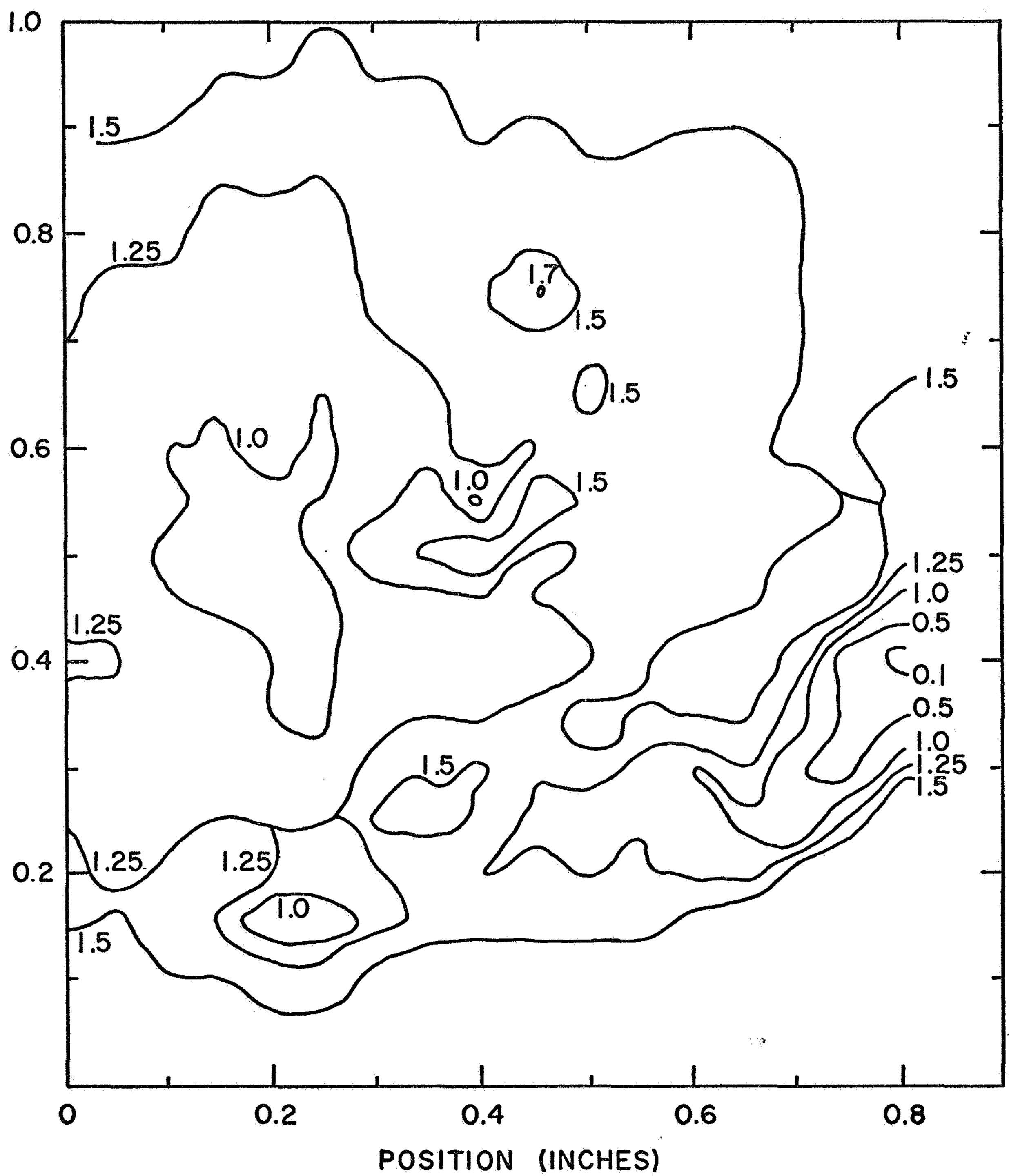

FIGURE I

EQUITRANSIT TIME CURVES VERSUS POSITION ON AN RCA 7265 PHOTOMULTIPLIER CATHODE. CONTOUR DESIGNATORS REFERS TO RELATIVE TIME DELAY IN NANOSECONDS.

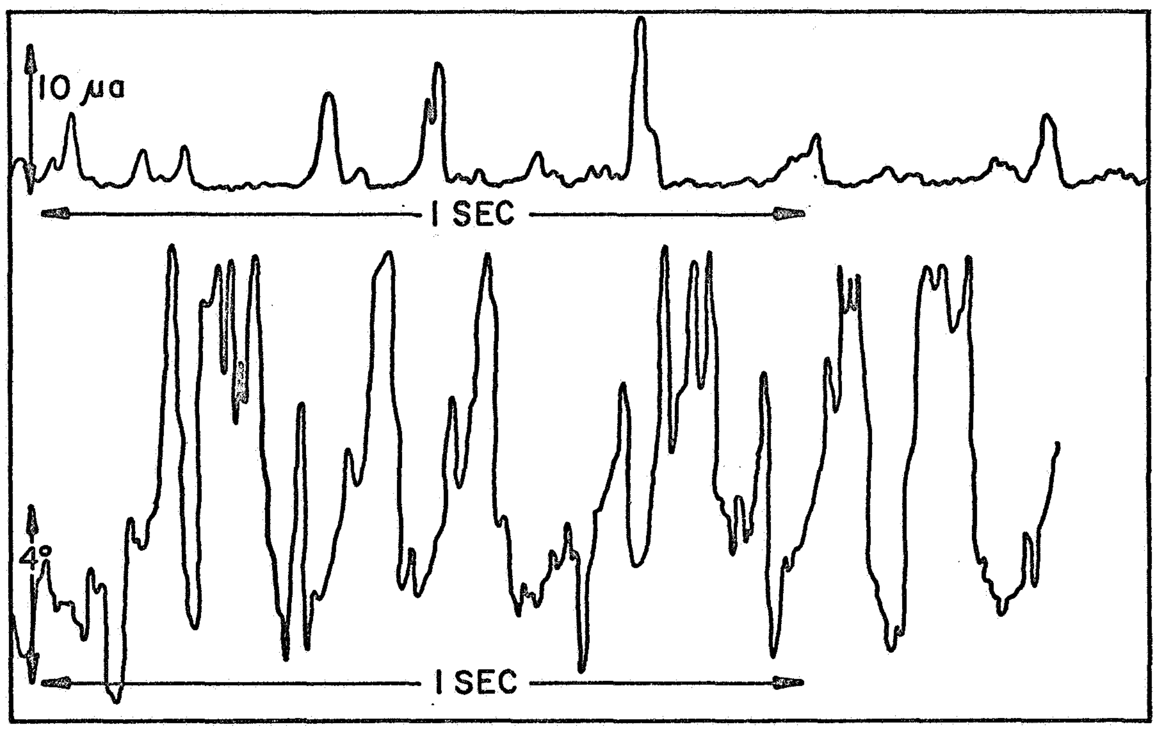

FIGURE 2

TYPICAL TIME VARIATIONS IN SIGNAL STRENTH AND PHASE RESULTING FROM ATMOSPHERIC TURBULENCE.

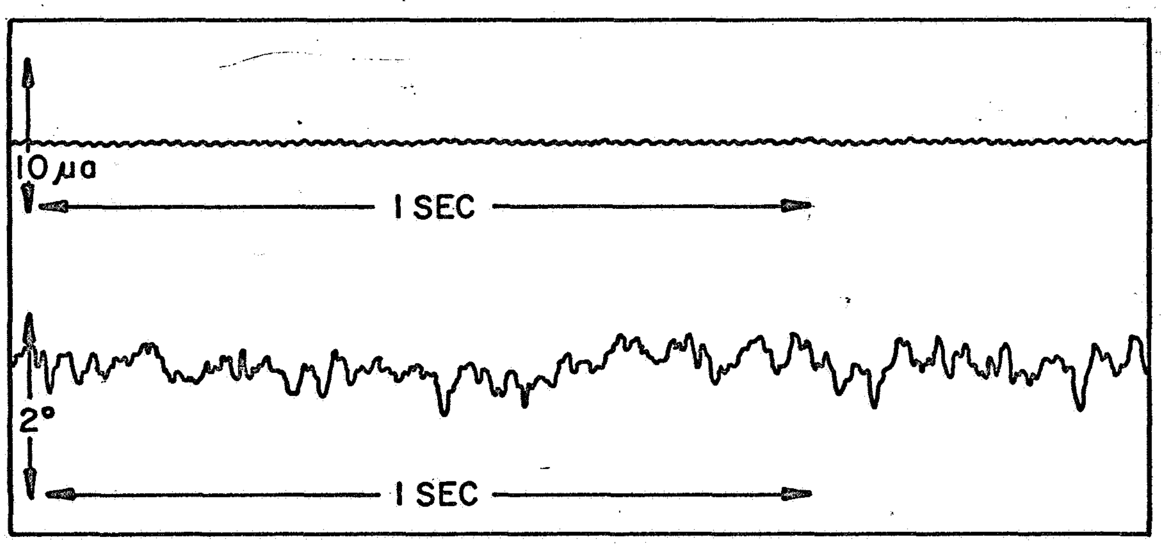

FIGURE 3

TYPICAL TIME VARIATIONS IN SIGNAL STRENGTH AND PHASE INDEPENDENT OF ATMOSPHERIC TURBULENCE.